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U. S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

ENGINEERING DEVELOPMENT LABORATORY

REPORT NO. NADC-ED-L6291 12 DECEMBER 1962

DIGITAL TRANSDUCER RESEARCH PROGRAM, 5935-M
FINAL REPORT

BUREAU OF NAVAL WEAPONS
WEPTASK NO. R360FR102/2021/R01101001
(FORMERLY TED PROJECT ADC-RS-7045)

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S U M M A R Y

INTRODUCTION

There are two good reasons for digitizing signals representing some physical dimension which exists continually in time and space. First, data in digital form are required by digital control computers and by digital data logging, data processing, and data transmission equipment. Second, digital data can be stored for any length of time, transmitted over any distance, retransmitted, detected, and read as many times as necessary with no loss in accuracy. Analog signals are distorted by each of these processes causing a loss in accuracy. From the standpoint of accuracy, if data are to be digitized at all, the digitizing should be done as close as possible to the point of measurement, and preferably within the transducer itself.

A method was conceived to transform transducer rectilinear motion into a parallel binary pulse code by magnetic techniques. This non-contact technique generates digital signals representing the mechanical displacement of a magnetic armature, by successively altering the state of a matrix of magnetically permeable wire rods. The rods of the matrix are inductively coupled to the armature by an alternating or pulsed magnetic field. Sense windings about the rods are cross connected to provide the desired codes.

Briefly, the magnetic technique uses the variation in the magnetic field strength about the magnetic rods and the binary connected sense windings to generate two-level voltage signals. The negative signals are then designated as binary "zeros" and the positive signals as binary "ones." The signals are generated in response to the relationship of an a.c. excited magnetic armature to the matrix of magnetically permeable rods. The series connected sense windings about the rods form a binary coded pattern representing the rectilinear displacement of the armature. A more detailed description of the magnetic technique is presented in reference (a).

SUMMARY OF RESULTS

A theoretical analysis of the digital magnetic technique revealed that the limit of resolution is 0.004 inch armature travel per bit when using 0.010-inch diameter matirx rods. The limit of resolution is 0.002-inch armature travel per bit when using 0.005-inch diameter matrix rods.

The theoretical analysis revealed that only essential sense windings in a given digit, those adjacent to a zero-one transition, require a large number of turns. Sense windings of several turns in the other locations are adequate to sustain the signal between transitions.

Experimental matrices having a resolution of 0.004 of an inch armature travel per bit were successfully fabricated. The binary digit of these units were uniform within 10 percent of each other.

A seven-bit absolute digital altitude transducer was designed and fabricated. The transducer had a resolution of 0.013 of an inch armature travel per bit and a range of 0 to 23,000 feet. The transducer had an accuracy of ± two-bits at laboratory ambient temperature. Of this, ± one-bit is the quantizing error and ± one-bit is the hysteresis error. When exposed to temperature extremes of -10 and 70 degrees C., the digital output indicated 1,500 feet low and 600 feet high, respectively. When checked for repeatability, the transducer indicated within ±75 feet of the selected altitude.

The average period of uncertainty during a zero-one transition was 21.4 feet. This value can be reduced to 3.5 feet by the use of a sensitive amplifier.

CONCLUSIONS

A matrix with a resolution of 0.002 inch armature travel per bit cannot be achieved with present manual techniques. However, with the gradual improvement of materials and the establishment of automatic techniques for matrix fabrication, this limit of resolution is possible.

Matrices having a resolution of 0.004 inch of armature travel per bit are feasible. A transducer with this resolution requires an armature travel about one-half inch for seven bits. This is approximately two and one-half times the design objective of three-sixteenths inch armature travel for seven bits.

The two percent accuracy achieved in the experimental digital transducer is not adequate for most applications. However, with the selection of a more accurate and complete compensation of the matrix, a digital transducer with an accuracy of one percent can be made.

The large shift in digital output resulting from temperature change is undesirable in a transducer. It is believed that this discrepancy can be remedied by temperature compensation of the aneroid capsule and the matrix.

RECOMMENDATIONS

A development program should be established to improve the resolution and the temperature characteristics of the digital transducer as well as to improve the design for reliable operation in a military prescribed environment. The application of the magnetic technique to other types of transducers should also be investigated.

Very little, relatively, is being done by the government or industry in research and development in the field of digital transducers. It is highly recommended that efforts are made to apprise all activities of the importance of the field so that greater interest and effort will be brought to bear on the creation of basic digital transducers.

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THEORETICAL ANALYSIS

Equations were derived in reference (a) which approximate the output signal from single sense winding and from a matrix of series connected sense windings in response to the movement of an armature. The equation representing the signal output of a single sense winding is:

$$E_n = \frac{E_o}{\left(\frac{rn}{L_o}\right)^2 + 1} \tag{1}$$

where

E_o = the output of an armature aligned sense winding.

E_n = the output of a sense winding n rods either side of the armature aligned rod.

n = the number of the rod referenced to the armature aligned rod.

r = the matrix resolution.

L_o = the mean magnetic path length between the armature and the armature aligned sense winding.

The equation representing the output signal, E, of a matrix of series connected sense windings is:

$$E = \sum E_n. \tag{2}$$

Equations (2) and (3) were used to determine the limits of resolution, when resolution is denoted as the minimum armature movement which produces a measureable response in the matrix output. The equations were written for the last significant digit (LSD) of a seven-bit matrix and evaluated with the armature located at rod number 63 of the 128 rod matrix. The output ratios, E_1/E_o, the single sense winding output and, E/E_o, the matrix output, were plotted against r/L_o, a function of the resolution, in figure 1. Since L_o is a constant for a particular matrix design, the curves represent the response of the output signal as a function of resolution. It can be observed that a knee occurs in the curve representing the matrix output when the ratio $(rn/L_o)^2$ is much less than unity. This knee indicates that the LSD of the code looses definition and is therefore the limit of resolution for the digital magnetic technique. The value of rn/L_o at this point is 0.33. The ratio of E_1/E_o is 0.9 when rn/L_o is equal to 0.33. Thus, the limit of resolution can then be defined in terms of output voltage as the rectilinear armature displacement causing a 10 percent drop in the maximum output signal, E_o, of a sense winding.

The limit of resolution in terms of armature displacement is 0.004 inch of armature travel per binary digit when the matrix is composed of 0.010-inch diameter rods wrapped with 0.003-inch diameter sense windings. A seven-bit matrix with this resolution would necessitate an armature travel of 0.512 inch. Experiments corroborated the limit of resolution for the 0.010-inch diameter matrix rod. Further analysis revealed that the limit of resolution is 0.002 inch of armature travel per binary digit when the matrix is composed of 0.005-inch diameter rods wrapped with 0.001-inch diameter sense windings. Attempts to manually fabricate a matrix of 0.005 inch rods were unsuccessful because of the low tensile strength of the sense winding material. A seven-bit matrix employing this resolution would require an armature travel of 0.256 inch. This armature travel approaches the design objective of seven bits for an armature travel of three-sixteenths inch. With the continual improvement of materials and fabrication by automatic techniques, a matrix having a resolution of 0.002 inch per bit should be a reality in the near future.

MATRIX DESIGN

The theoretical analysis of the seven-bit transducer also revealed that some of the sense windings between adjacent "zero-one" transitions of the same binary digit did not influence the output signal. It was noted that the signals from the sense windings in these locations on one side of the armature were cancelled by signals from sense windings in similar locations on the other side of the armature. Consequently, it can be concluded that the only essential sense windings in a given digit are those adjacent to a "zero-one" transition. Empirically, it was determined that a sense winding of several turns is required in these locations to sustain the proper signal magnitude between the transitions. This innovation greatly simplified the fabrication of the matrix and did not contribute to any deficiency in the output signal.

MATRIX COMPENSATION

When the armature is operated at either end of the matrix, fewer rods and sense windings are encompassed by the magnetic field causing deviations in the output signal. The analysis revealed that this end-effect deviation can be compensated by altering the sense winding turns ratios of the three least significant digits at both ends of the matrix. The compensation of these digits at the occurrence of their first and last "zero-one" transitions eliminated the end effect deviation. The higher order digits did not contribute to the end-effect deviation.

The pulse generator in the system provides the excitation to the armature; the pulse amplifiers and shapers transform the matrix output pulses to a form compatible with an oscillograph recorder. The pulse generator continuously excites the armature with 20 volt, 3 microsecond pulse at a repetition rate of 30 kilocycles. The matrix provides a continuous output of 3 microsecond pulses at a repetition rate of 30 kilocycles for

each digit. A binary "zero" is represented by negative pulses having an amplitude of 15 millivolts and a binary "one" by positive pulses having an amplitude of 15 millivolts. The matrix output signals are amplified, transformed and recorded on an oscillograph as a d.c. level.

DIGITAL PRESSURE TRANSDUCER

The operational capabilities of the magnetic technique were demonstrated by the design of a seven-bit or altimeter. The aneroid pressure capsule from the AN/AMT-11A Radiosonde positions the armature within the matrix. The seven-digit binary output represents an altitude change from sea level to 23,000 feet for an armature travel of 1.25 inches. Although the aneroid capsule has a full scale range of 120,000 feet, the reduced range was utilized to facilitate the evaluation of the transducer. Since the fabrication of the transducer matrix was started before the theoretical analysis had been completed, the resolution of the operational unit was 0.013 of an inch armature travel per bit rather than the minimum 0.004 of an inch armature travel per bit. A photograph of the digital transducer and associated components is shown in figure 2. The seven-bit matrix is shown in figure 3. The detailed characteristics of the transducer are outlined in appendix A.

MATRIX OUTPUT SIGNAL

Typical outputs of the two LSD's of a matrix are illustrated in figure 4. The LSD output for a binary "one," a period of uncertainty, and a binary "zero" are illustrated in figures 4(a)1, 4(a)2, and 4(a)3, respectively. The period of uncertainty is defined as the armature location during a transition which produces a matrix output signal representing neither a "zero" nor a "one." The outputs of the respective amplifiers for the three signals are shown in figures 4(b)1, 4(b)2, and 4(b)3. The amplifier output of the next higher digit is shown in figures 4(c)1, 4(c)2, and 4(c)3 for all signal phases of the LSD. It is apparent that there is no perceptible indication of crosstalk between these digits. The same is true for the other higher order digits.

Typical matrix outputs during the period of uncertainty are illustrated in figure 5. Uncertain matrix outputs are shown in figures 5(a)1 and 5(a)2. Figure 5(a)3 illustrates a matrix output representing a binary "one." It is evident from the illustrations that a slight difference in signal amplitude exists between a defined output and the period of uncertainty. The amplifier output of the changing signals is shown in figures 5(b)1, 5(b)2, and 5(b)3. The output of the next higher order digit is shown in figures 5(c)1, 5(c)2, and 5(c)3 for all phases of the LSD.

Tests were conducted to determine the width of the period of uncertainty in terms of altitude change and armature displacement. The period of uncertainty was determined by comparing the length of oscillograph record required for an altitude change of 100 feet to the length of the record for a zero-one transition for a constant altitude change. The average period of uncertainty was 21.4 feet. When a more sensitive digit amplifier was used in the least significant digit, the average period of uncertainty was reduced to 3.5 feet. The transducer calibration established the LSD to be equivalent to 180 feet, then the period of uncertainty in terms of armature travel is 15.4×10^{-4} inches. When the sensitive digit amplifier is used, the period of uncertainty in terms of armature travel is 2.5×10^{-4} inches. Although the period of uncertainty is evident on an oscilloscope, the error resulting from this condition is well within the one-bit quantizing error.

CALIBRATION

The digital transducer was calibrated to determine the relationship between the altitude and the diaphragm movement and the relationship between the altitude and the digital output. In order to make the first calibration, a small mirror was secured to the armature pivot arm and a light beam reflected on a scale in the same manner as a general laboratory D'Arsonval galvanometer. A calibration of altitude versus deflection was prepared and it was observed that the aneroid capsule contained a hysteresis error of ± 180 feet. A mercury manometer was used as a calibration standard.

A calibration of altitude versus binary code was prepared. Since the Gray code output of the transducer is a nonweighted code, the equivalent natural binary code was calibrated and weighted with respect to altitude. The calibration of the seven-bit code is listed in table 1. The transducer was calibrated for sea level and all laboratory readings must be corrected by adding 350 feet.

A typical oscillograph recording of the output of the digital transducer is illustrated in figure 6. In addition to the seven traces, one for each binary digit, the recording also includes an analog trace representing manometer pressure in inches of mercury. Pulses on the analog trace represented intervals of two inches of mercury. Figure 6 represents the transducer output for a pressure change from 28 to 12 inches of mercury, which corresponds to an altitude change from 1,000 to 24,000 feet. To determine the indicated altitude, the digital number was read from the recording, the Gray code transformed to the natural binary code using appendix B and then the weights of table 1 used to obtain the altitude. This operation is illustrated in table 2 for several of the pressure points on figure 6. In practical application, the transducer calibration data would be part of the digital system and the entire transformation performed automatically.

The hysteresis and repeatability of the transducer is illustrated in figure 7, a section from two repeated calibrations. The altitude of each "zero-one" transition is indicated over a range of 2,000 feet for both ascending and descending readings. In order to determine the source of the hysteresis, a calibration was made of the output code with respect to the light spot scale. Since the light spot scale is an indication of the armature location, with respect to the matrix, only the hysteresis due to the coding technique would appear in this calibration. Figure 8 shows that the hysteresis contribution of the armature and matrix was negligible. Only the transition between matrix rods 51 to 52 indicate a difference of more than 0.02 inch light scale (approximately 30 feet altitude) between ascending and descending readings.

VIBRATION TESTS

The transducer was subjected to limited vibration of the type used to negate friction of sensitive instruments. For the most part, the effect of this vibration was insignificant. However, on several "zero-one" transitions, the amplifiers were triggered into oscillation and increased the period of uncertainty by 50 to 100 percent. This error is well within the quantizing error of ±one-bit. It is believed that the amplifiers were triggered into oscillation by the armature coming into contact with a matrix rod. This condition can be remedied in later models by coating the face of the matrix with varnish.

TEMPERATURE TESTS

The digital transducer was evaluated at -10 and at 70 degrees C. While subjected to cold, the transducer indicated 1,500 feet low and the hysteresis error increased to ±300 feet. While subjected to high temperature, the transducer indicated 600 feet high and the hysteresis error decreased to ±75 feet. These errors can be attributed to the fact that the aneroid capsule is inadequately compensated for the pressure range in which it was used. The high hysteresis error during cold can be attributed to the heavy precipitation of snow on the matrix when air was admitted to the cold chamber for the return to ambient pressure.

HUMIDITY

The digital transducer was saturated with moisture and the device operated satisfactorily even with the armature traversing the matrix in a film of water.

THERMAL AND PHYSICAL SHOCK

Several matrices and armatures were subjected to thermal and physical shock without any noticeable damage. The units were soaked for one hour at -65 degrees C. and then placed on a hot metal plate in an oven at 66

degrees C. to determine if the thermal shock would crack the expoxy or damage the sense windings. One of the matrices chipped slightly around one of the mounting holes, but this was credited to damage during previous handling. The devices were also subjected to a 100g. shock having a duration of 11 milliseconds and no difficulties were experienced.

APPLICATIONS OF THE DIGITAL MAGNETIC TECHNIQUES

A transducer design employing a divided matrix was conceived which would provide a resolution of 0.002 inch armature travel per bit by utilizing two matrices, each having a resolution of 0.004 inch armature travel per bit. In the application, the armature is an integral part of the sensor as illustrated in figure 9(a).

The sense windings of one matrix section are wound in the normal manner. Another binary digit is obtained from a second section by providing two windings similar to the least significant digit of the first section. These two windings would yield a signal as indicated in figure 9(b). When the two output signals are summed, the resulting three level signals, as shown in figure 9(b), represent a new least significant digit having twice the resolution of the old digit. In application, the second matrix section would be offset one-half a resolution with respect to the first matrix section to conform with the Gray code.

Additional transducer types are illustrated by sketches in figure 10. The first sketch, figure 10(a), represents a more compact version of the experimental digital pressure transducer design utilizing a matrix resolution of 0.004 inch. The experimental model digital altitude transducer had a design matrix resolution of 0.013 inch to avoid a major modification of the radiosonde transducer. Figure 10(a) is an application with the armature as an integral part of the sensing unit. A digital accelerometer is illustrated in figure 10(b). The weighted armature is restrained by a flat spring and damping fluid. The range is a function of the weighted mass and the strength of the spring. A one "g." accelerometer may be used as a leveling device. A bimetal strip substituted for the flat spring will change the accelerometer design to a temperature transducer.

Liquid expansion and vapor pressure sensors used in existing temperature indicators may also be used to provide the rectilinear displacement for a temperature transducer.

REFERENCES

(a) NAVAIRDEVCEN Report No. NADC-ED-6127, "Digital Transducer Research Program, 5935-M, Second Annual Progress Report," of 1 Aug 1962

Table 1. Calibration of Digital Altitude Transducer in the Form of Weighted Natural Binary Digits

Binary Digit	Weight (Ft.)
1	180
10	361
100	708
1,000	1,434
10,000	2,864
100,000	5,718
1,000,000	11,578

Table 2. Examples of Code Conversion Into Altitude With Weighted Natural Binary Digits

Reading From Oscillogram (Fig. 9)			Conversion	Result	Error
In. Hg.	Standard Altitude Feet	Gray Code	Natural Code	$\sum$1's + 350 ft.*	Feet
26	3,834	11,010	10,011	3,755	79
24	5,974	10,000	11,111	5,897	77
22	8,262	111,110	101,011	8,043	219
20	10,726	100,101	111,000	10,546	180
18	13,399	1,100,100	100,111	13,177	222
12	23,198	1,000,001	1,111,110	23,193	5

*The zero was offset 350 feet to include full matrix output

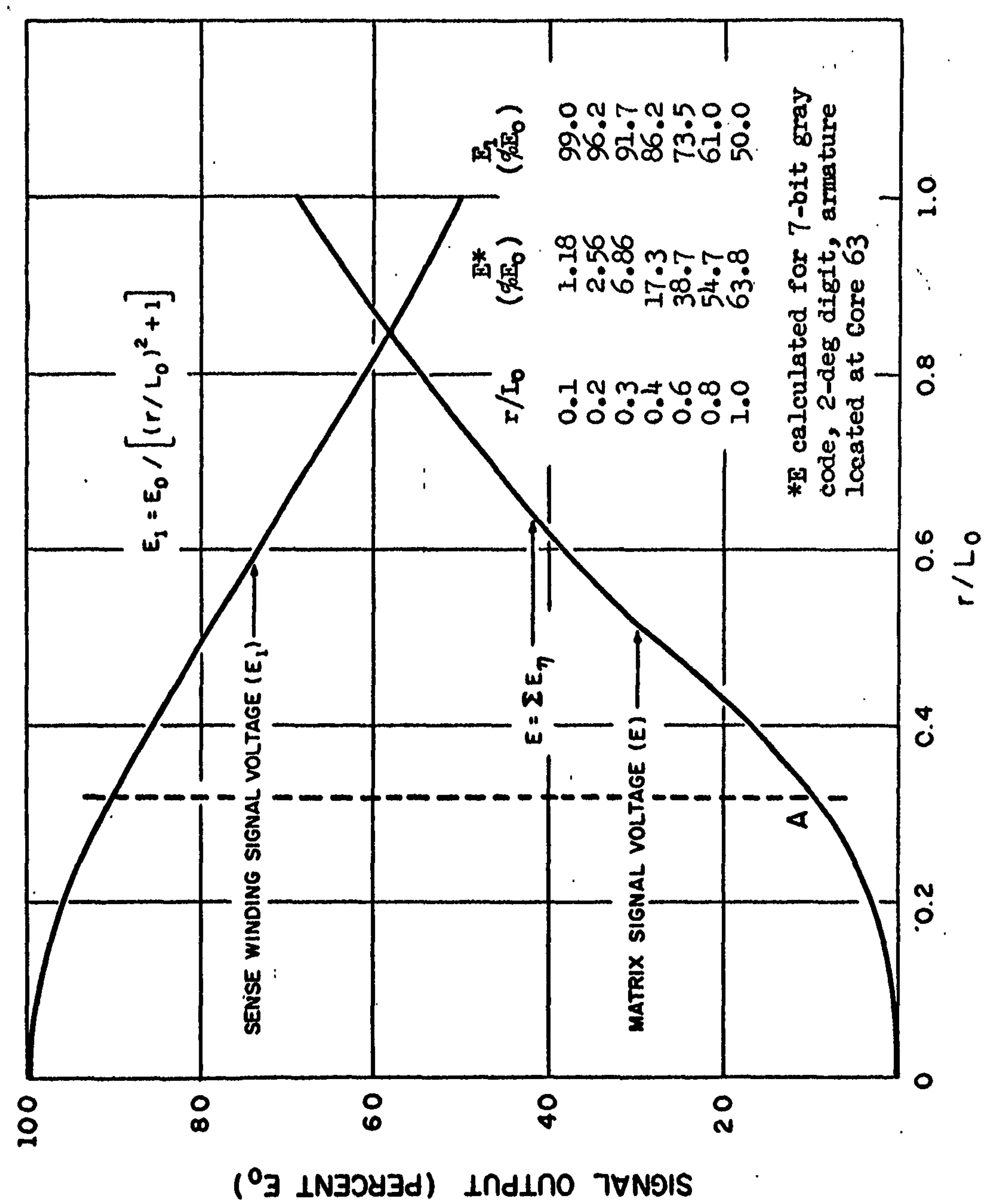


Figure 1. Comparison of Matrix Signal (E) and Sense Winding Signal (E_1)

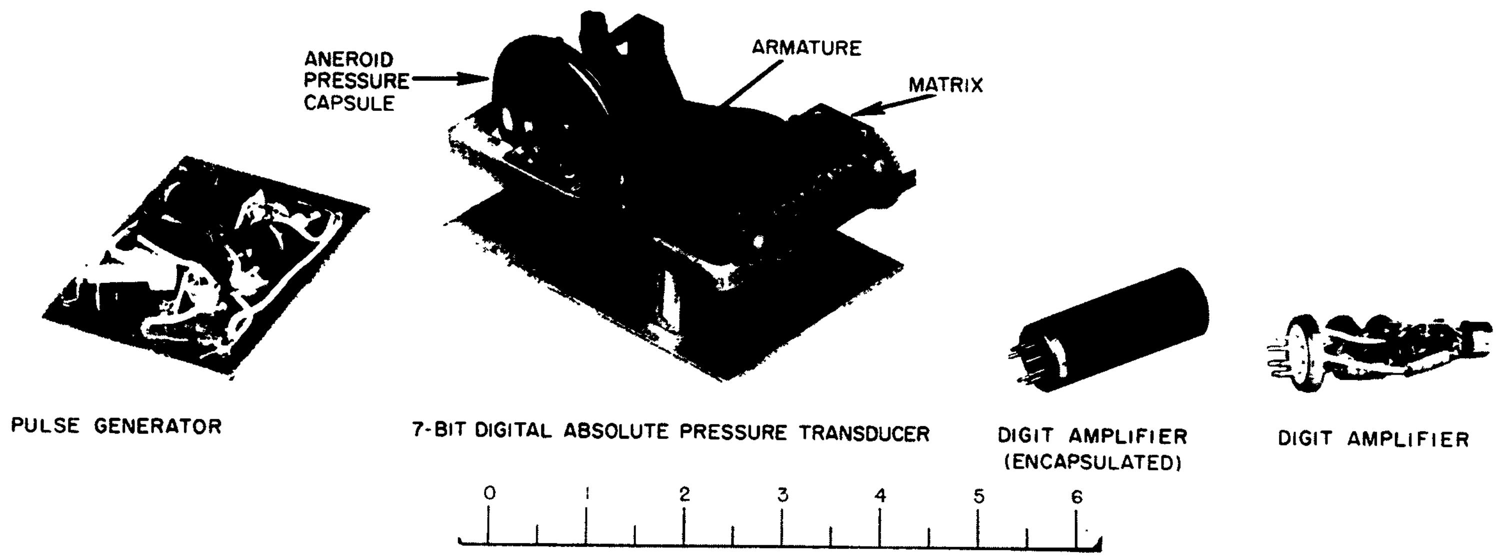


Figure 2. Digital Altitude Transducer System

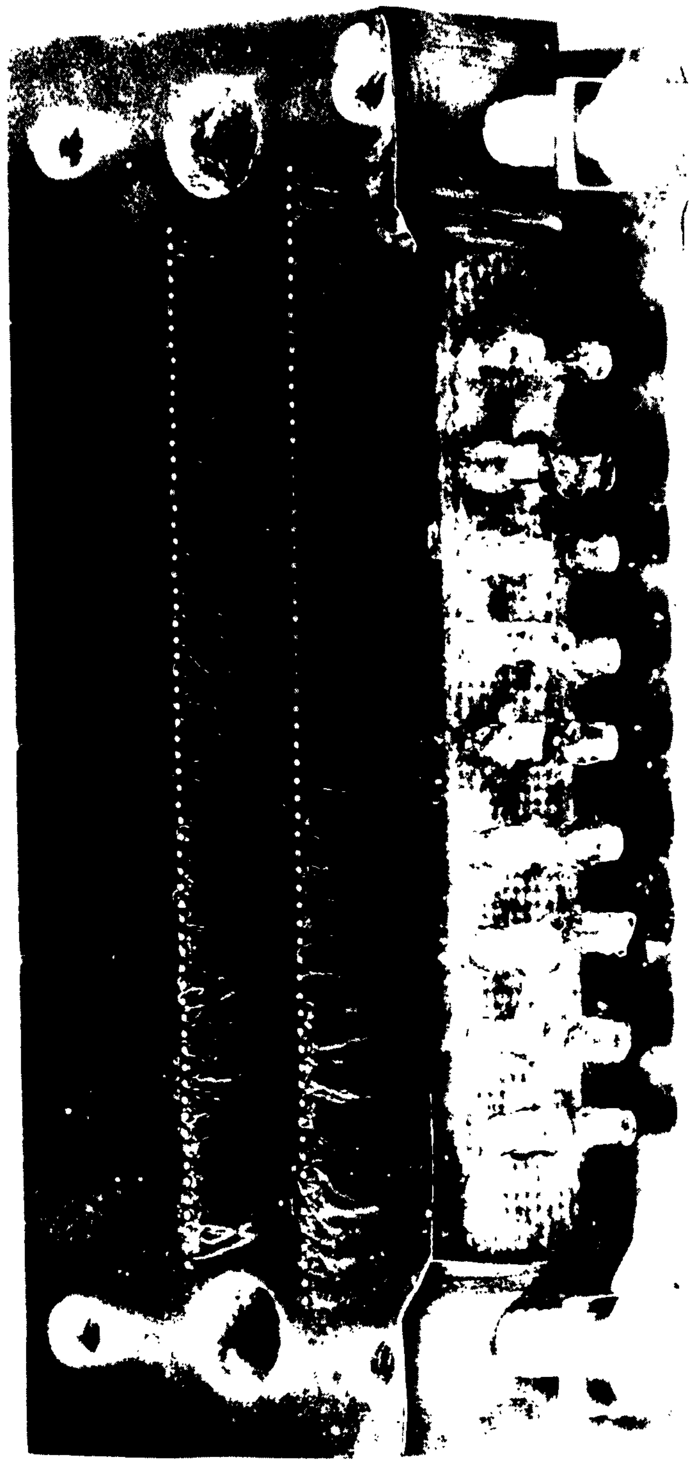


Figure 3. Matrix Digital Altitude Transducer

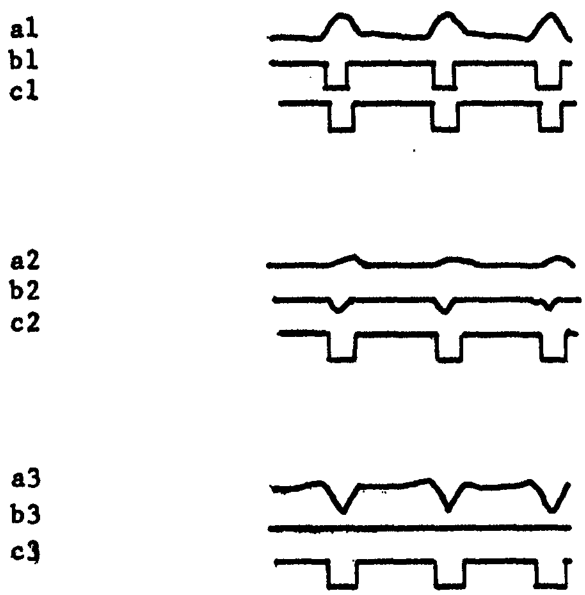


Figure 4. Matrix and Amplifier Output Signals

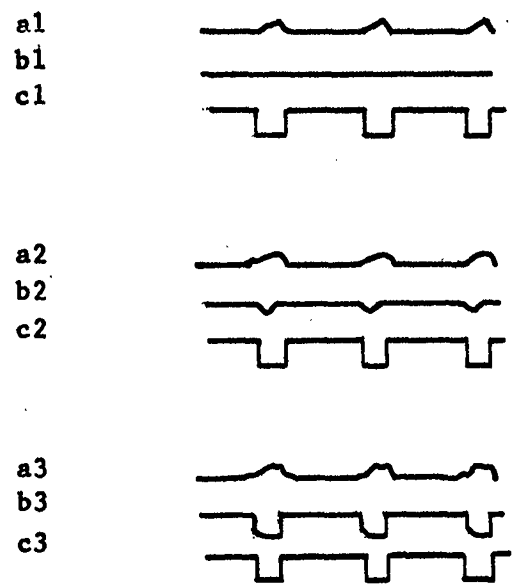
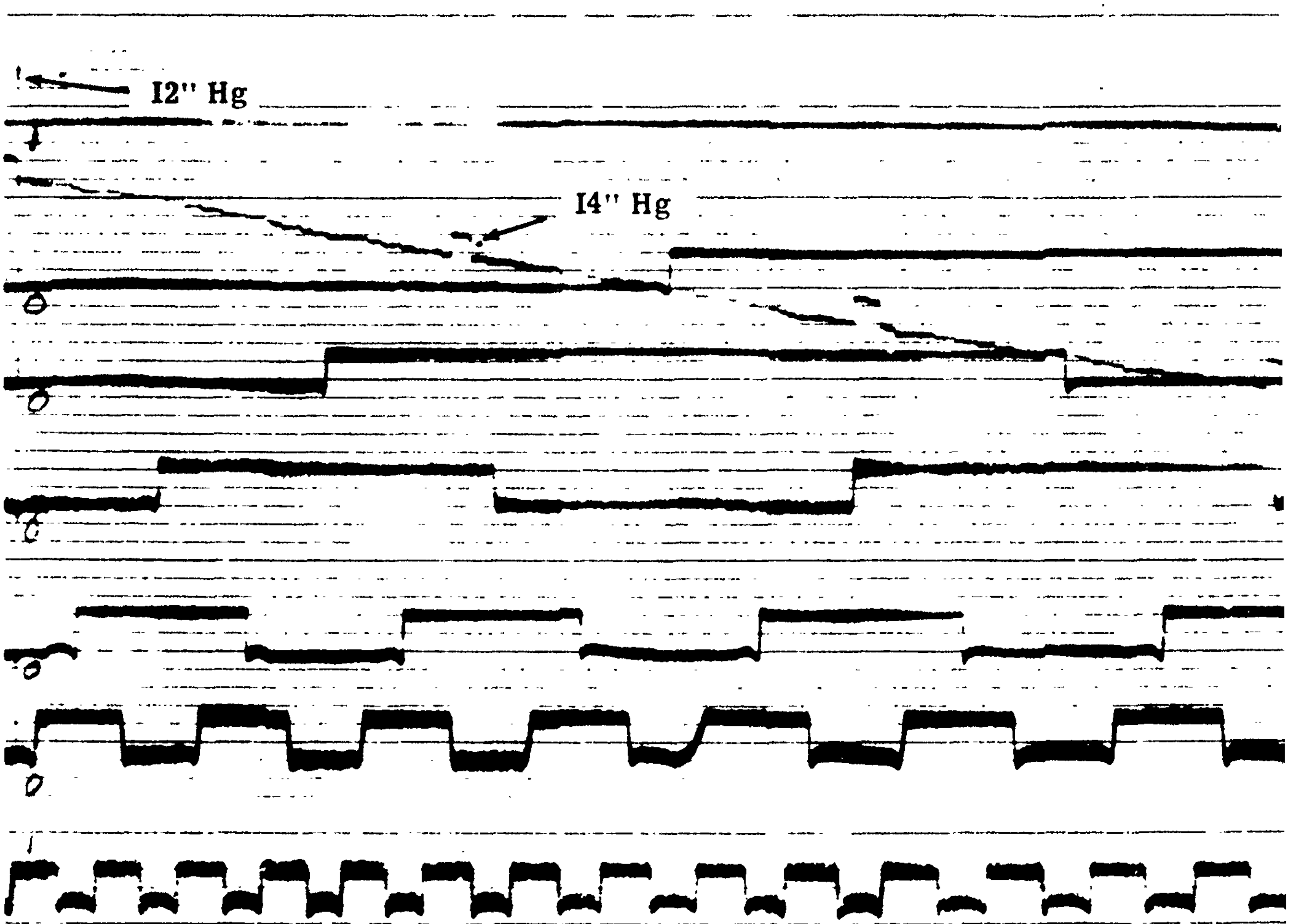


Figure 5. Matrix Output Signal During a Code Transition

1



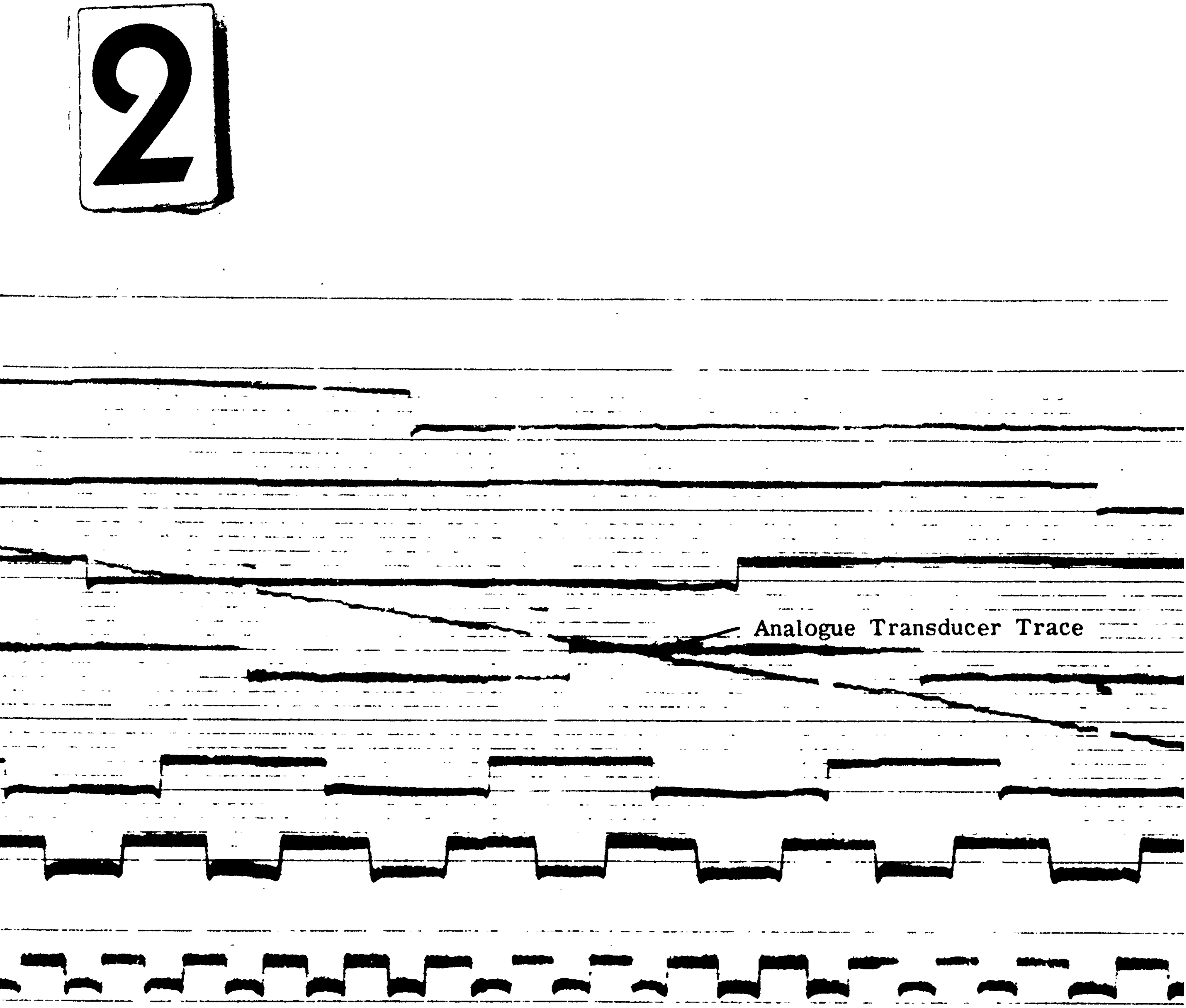


Figure 6.

3

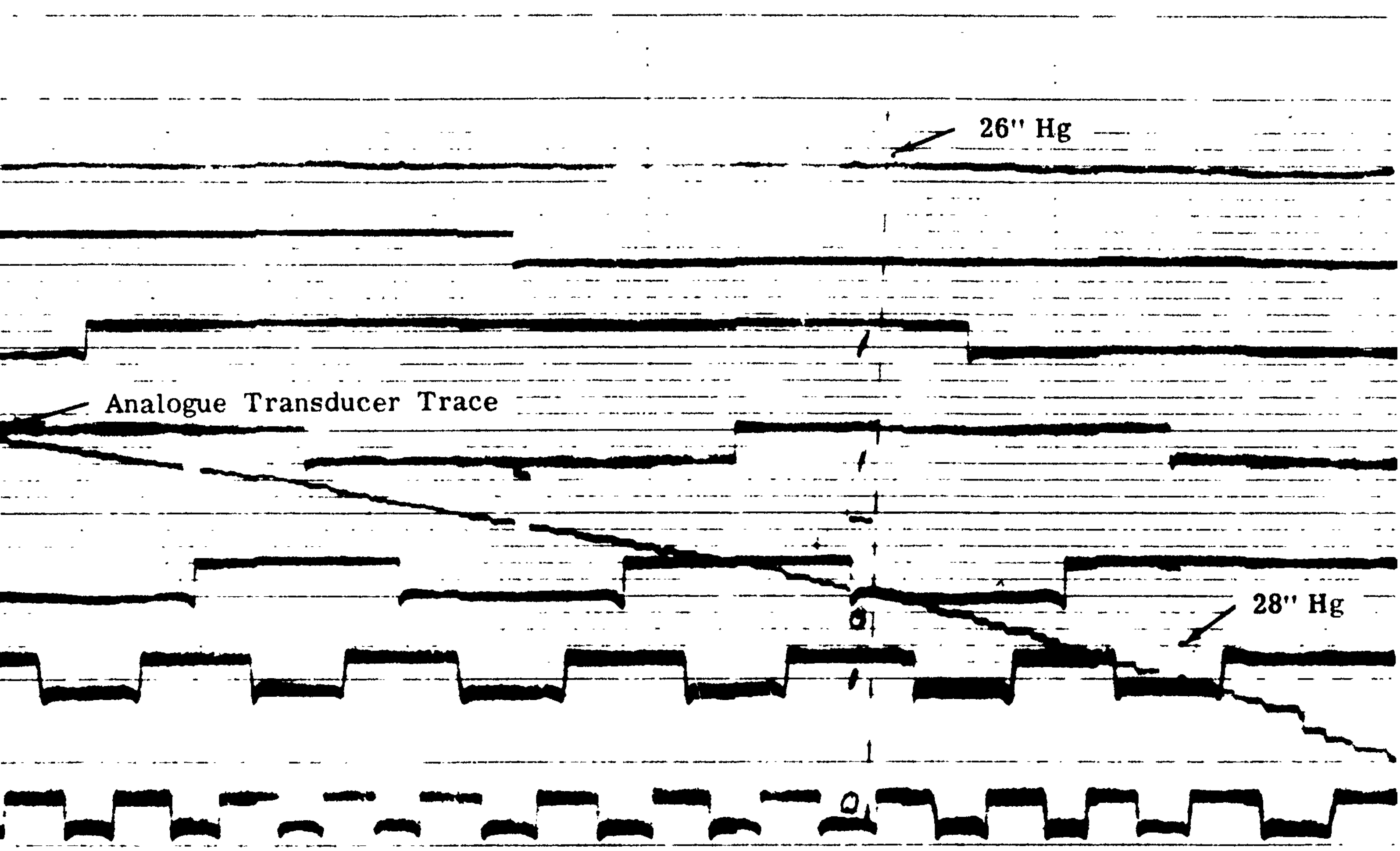


Figure 6. Oscillograph Record of Matrix Output

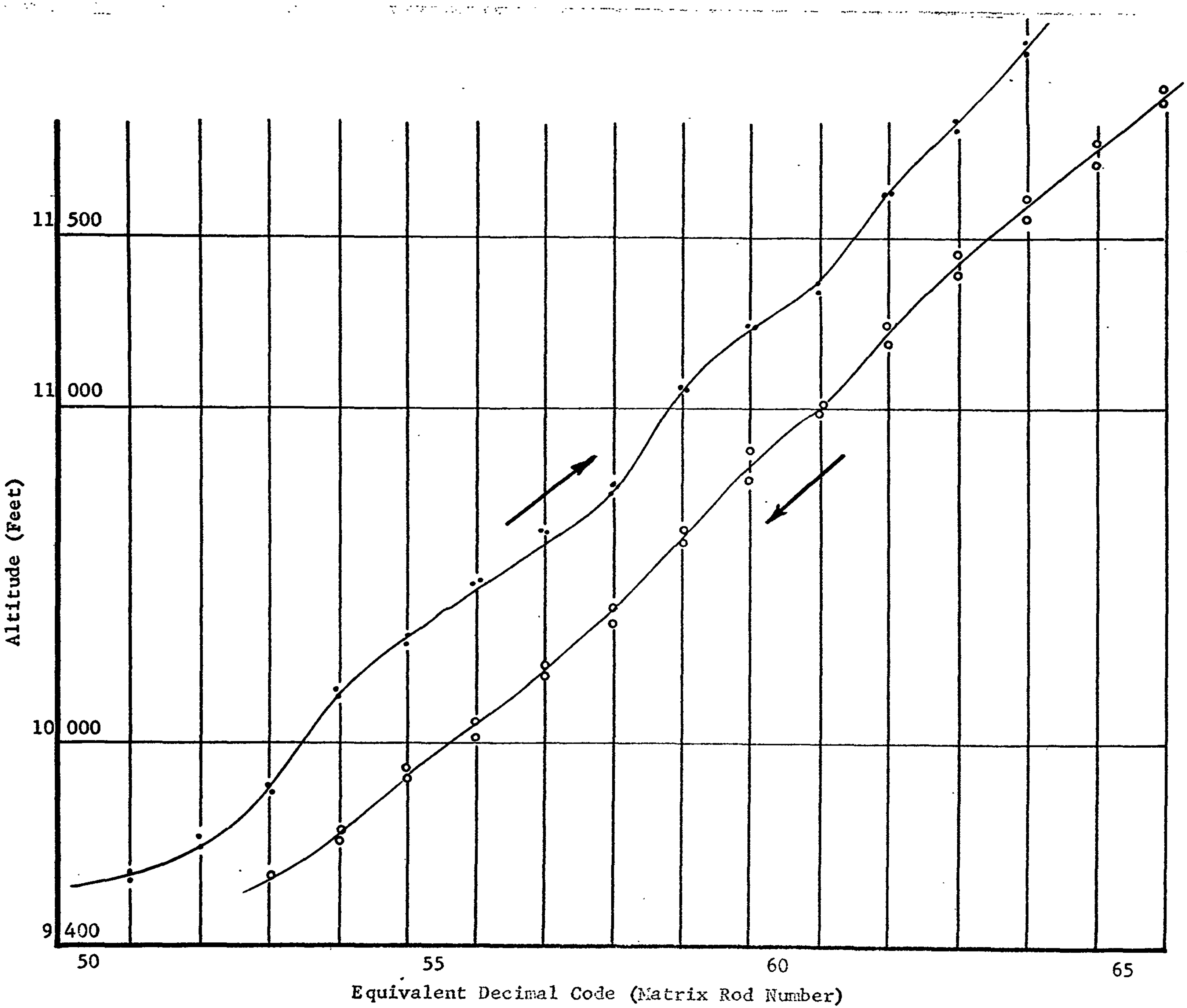


Figure 7. Hysteresis and Repeatability Digital Altitude Transducer

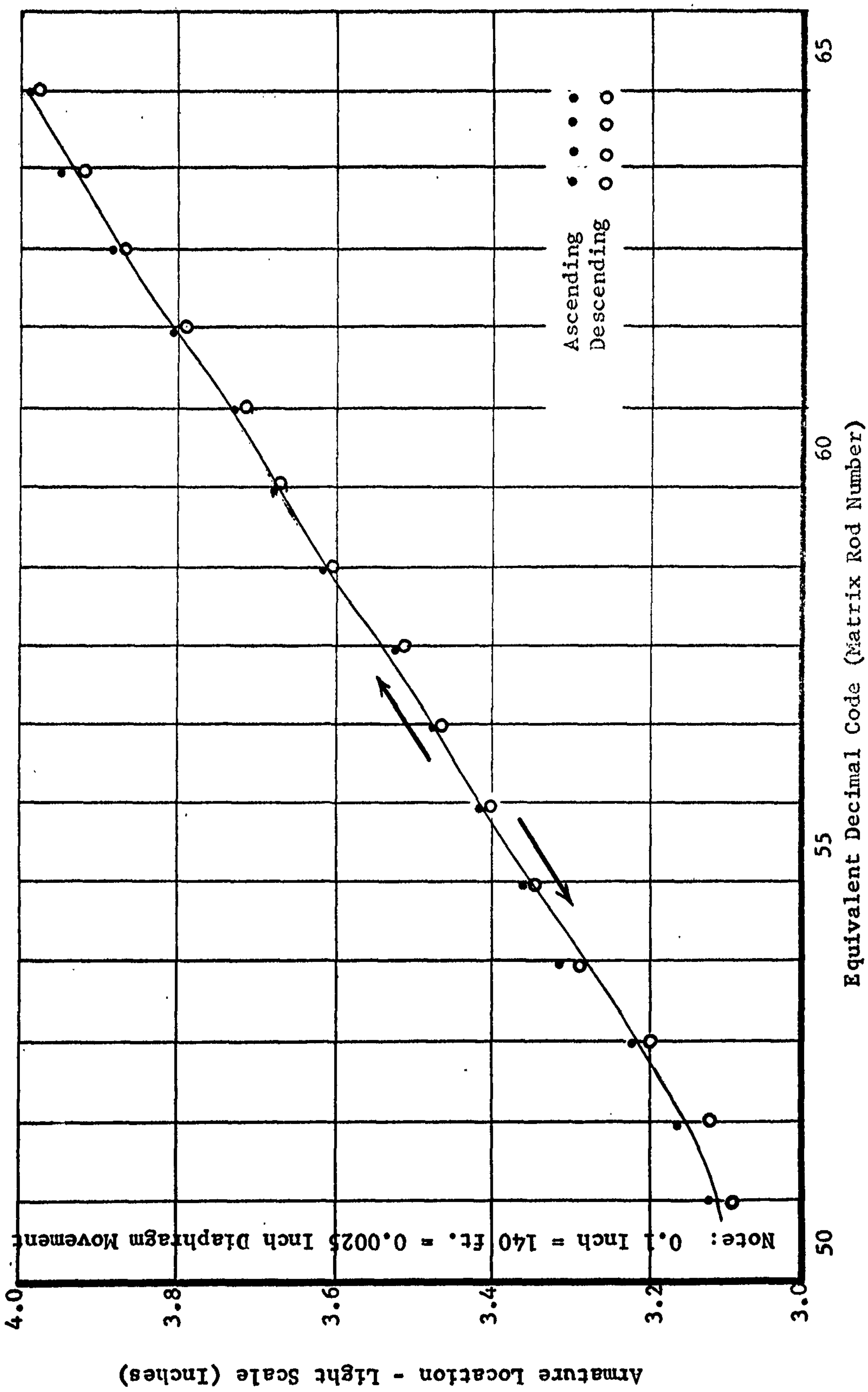
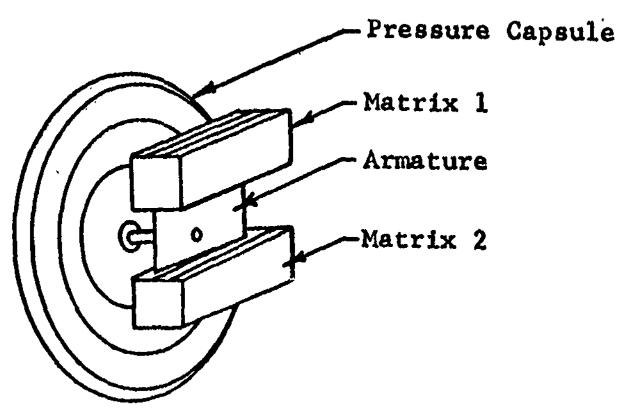
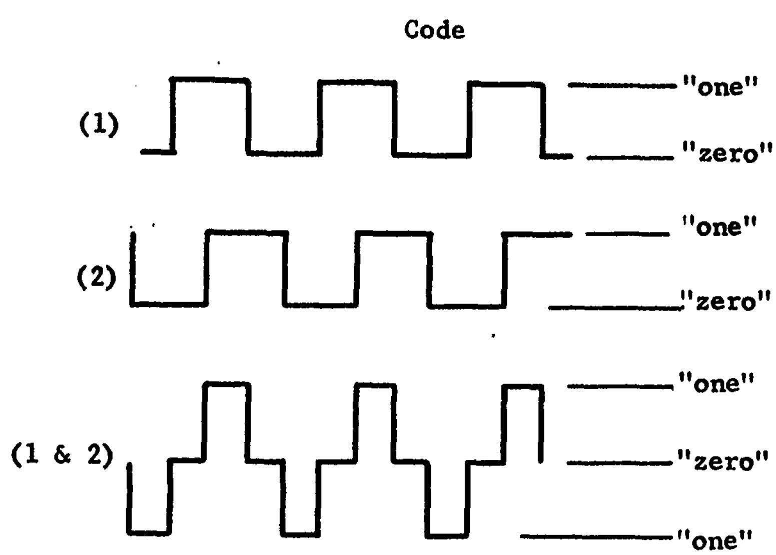


Figure 8. Armature Location Vs. Matrix Output Signal



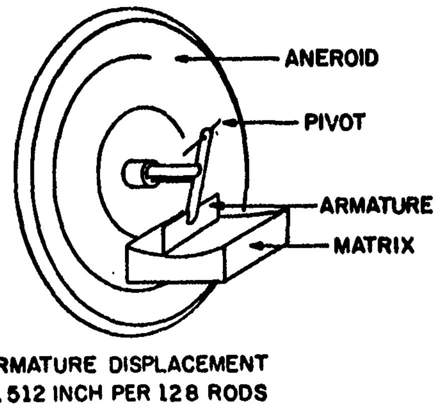
(a) Divided Matrix



(b) Matrix Signal

Figure 9. Application of the Divided Matrix

(a) Pressure Transducer



(b) Accelerometer Transducer
(Enclosed in Damping Fluid)

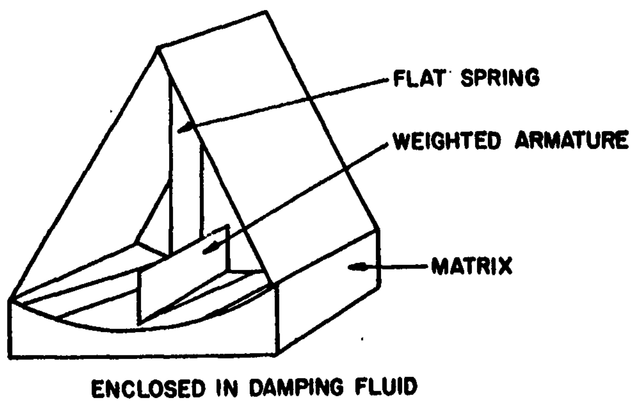


Figure 10. Additional Transducer Applications

APPENDIX A - CHARACTERISTICS OF EXPERIMENTAL DIGITAL ALTITUDE TRANSDUCER

Type: Digital magnetic

Range: Variable 0 to 23,000 feet or 0 to 100,000 feet

Temperature Range: 0 to 50 degrees C.

Output: 7 binary digits (parallel)

Shock (non-operating): 100g. at 11 milliseconds

Vibration: Limited

Accuracy: ±2 bits; ±360 feet

Hysteresis: ±180 feet

Repeatability: ±75 feet

Period of Uncertainty: 21.4 feet average

Resolution: 1 part in 128

Input Pulse: Repetition rate: Single pulse to 50 kilocycles
Width: 3 to 10,000 microseconds
Amplitude: 10 to 50 volts

Armature: D.C. resistance - 50 ohms
Inductance - 2 millihenries
Impedance -
Size: 0.6 X 0.2 X 0.06 inches (lwh)
Weight: 1 gram

Matrix: Maximum output signal $\pm$ 30 millivolts

Binary "one" - 5 millivolts

Binary zero - -5 millivolts

D.C. resistance - 50 ohms lsd

15 ohms other digits

Size: 2.3 X 0.7 X 0.4 inches (lwh)

Weight: 21 grams

Pulse Generator: Power - 28 volts d.c. at 50 ma.

Output pulse: variable -20 to 50 kc.

amplitude - 20 volts

width - 3 microseconds

Size: 3.0 X 2.2 X 0.5 inches

Weight: 25 grams

Digit Amplifiers: Power - 28 volts d.c. at 10 ma.

Input - 5 millivolts pulse - single pulse to 50 kc.

Output - 20 volt pulse

Output Impedance - 1,000 ohms

Size: 2.2 X 0.7 dia. inches

Weight: 5 grams

APPENDIX B - CONVERSION FROM BINARY TO BINARY GRAY

Decimal	Binary	Binary Gray	Decimal	Binary	Binary Gray
0	0	0	44	101100	111010
1	1	1	45	101101	111011
2	10	11	46	101110	111001
3	11	10	47	101111	111000
4	100	110	48	110000	101000
5	101	111	49	110001	101001
6	110	101	50	110010	101011
7	111	100	51	110011	101010
8	1000	1100	52	110100	101110
9	1001	1101	53	110101	101111
10	1010	1111	54	110110	101101
11	1011	1110	55	110111	101100
12	1100	1010	56	111000	100100
13	1101	1011	57	111001	100101
14	1110	1001	58	111010	100111
15	1111	1000	59	111011	100110
16	10000	11000	60	111100	100010
17	10001	11001	61	111101	100011
18	10010	11011	62	111110	100001
19	10011	11010	63	111111	100000
20	10100	11110	64	1000000	1100000
21	10101	11111	65	1000001	1100001
22	10110	11101	66	1000010	1100011
23	10111	11100	67	1000011	1100010
24	11000	10100	68	100010	1100110
25	11001	10101	69	1000101	1100111
26	11010	10111	70	1000110	1100101
27	11011	10110	71	1000111	1100100
28	11100	10010	72	1001000	1101100
29	11101	10011	73	1001001	1101101
30	11110	10001	74	1001010	1101111
31	11111	10000	75	1001011	1101110
32	100000	110000	76	1001100	1101010
33	100001	110001	77	10011101	1101011
34	100010	110011	78	1001110	1101001
35	100011	110010	79	1001111	1101000
36	100100	110110	80	1010000	1111000
37	100101	110111	81	1010001	1111001
38	100110	110101	82	1010010	1111011
39	100111	110100	83	1010011	1111010
40	101000	111100	84	1010100	1111110
41	101001	111101	85	1010101	1111111
42	101010	111111	86	1010110	1111101
43	101011	111110	87	1010111	1111100

Decimal	Binary	Binary Gray
88	1011000	1110100
89	1011001	1110101
90	1011010	1110111
91	1011011	1110110
92	1011100	1110010
93	1011101	1110011
94	1011110	1110001
95	1011111	1110000
96	1100000	1010000
97	1100001	1010001
98	1100010	1010011
99	1100011	1010010
100	1100100	1010110
101	1100101	1010111
102	1100110	1010101
103	1100111	1010100
104	1101000	1011100
105	1101001	1011101
106	1101010	1011111
107	1101011	1011110
108	1101100	1011010
109	1101101	1011011
110	1101110	1011001
111	1101111	1011000
112	1110000	1001000
113	1110001	1001001
114	1110010	1001011
115	1110011	1001010
116	1110100	1001110
117	1110101	1001111
118	1110110	1001101
119	1110111	1001100
120	1111000	1000100
121	1111001	1000101
122	1111010	1000111
123	1111011	1000110
124	1111100	1000010
125	1111101	1000011
126	1111110	1000001
127	1111111	1000000

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